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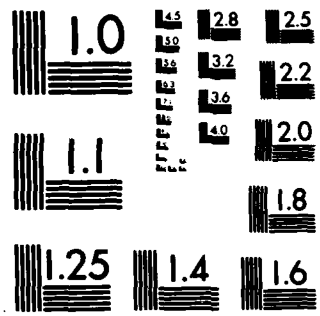

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ANNUAL TECHNICAL REPORT

MICROWAVE SEMICONDUCTOR RESEARCH - MATERIALS, DEVICES AND CIRCUITS

May 1, 1982 - April 30, 1983

CONTRACT # F49620-82-C-0083

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MICROWAVE SEMICONDUCTOR RESEARCH -

MATERIALS, DEVICES AND CIRCUITS

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WORK STATEMENT

TASK 1	Grow and characterize GaAs for high performance microwave devices.
TASK 2	Determine the effect of design and processing on GaAs power FET performance limitations.
TASK 3	Use MBE tailored profiles for improved GaAs power FET performance.
TASK 4	Investigate MBE multiple GaAs $Al_xGa_{1-x}As$ heterojunctions for confinement of electrons.
TASK 5	Develop high speed receivers for optical communication using optical field effect transistors and large area epitaxial photoconductive detectors.
TASK 6	Model and construct components and subsystems which can be useful as transmitters in optical communication systems.
TASK 7	Develop advanced design techniques for microwave GaAs FET amplifiers.
TASK 8	Improve direct method of broad band circuit design.
TASK 9	Use optical excitation to study carrier dynamics in compound semiconductors.
TASK 10	Study ballistic electron effects in transistors for high frequency operation.

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This program covers the growth and assessment of Gallium Arsenide, and related compounds and alloys, for use in microwave, millimeter, and optical devices. It also covers the processing of the material into devices, and the testing of the devices. Both molecular beam epitaxy (MBE) and organo-metallic vapor phase epitaxy (OMVPE) are used for growth. Materials assessment is included. Short modulation doped heterojunction transistors, as well as ballistic electron vertical FETs and heterojunction bipolar transistors, are covered. The following is a list of tasks pursued.

Task 1 Growth and characterization of GaAs for high performance microwave devices.

Task 2 Investigation of microwave field-effect transistor performance limits set by layer composition and contact geometry.

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Task 3 Use of MBE tailored profiles for GaAs power FET's for improved performance.

Task 4 MBE multiple GaAs-$Al_xGa_{1-x}As$ heterojunctions for confinement of electrons for improved FET performance.

Task 5 High speed receivers for optical communications.

Task 6 Dynamic and spectral characteristics of semiconductor laser materials and structures.

Task 7 Carrier dynamics in compound semiconductors studied with picosecond optical excitation.

Task 8 Advanced design techniques for microwave GaAs FET amplifiers.

Task 9 Wide band circuits and systems.

Task 10 (Ballistic task) Gallium arsenide ballistic electron transistors.

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TASK 1 GROWTH AND CHARACTERIZATION OF GaAs FOR HIGH PERFORMANCE MICROWAVE DEVICES

L.F. Eastman and D.W. Woodard

OBJECTIVE

The overall program objective is to develop an improved understanding of the role of the substrate and the growth parameters on the quality of device structures on GaAs and related materials grown by Organometallic Vapor Phase Epitaxy (OMVPE).

APPROACH

The approach to improve device quality materials grown by OMVPE centers around a fast feedback loop from data obtained from various characterization techniques and the actual growth parameters used during the deposition of epitaxial films. During this investigation an optimized process for various device structures of interest will be obtained using characterization data from low temperature photoluminescence (PL), deep level transient spectroscopy (DLTS), Hall and CV measurements, and other appropriate techniques. For example, a detailed understanding of the effects of the growth parameters on the optical and electronic properties of a GaAs/AlGaAs heterostructure will result in improved performance of some of the electron devices fabricated in other tasks in the JSEP program.

PROGRESS

Over the previous two years, Cornell has successfully designed and constructed a variable pressure OMVPE reactor for the growth of epitaxial III-V compound semiconductors. Until recently with the growth of GaInAs, the research effort at Cornell has centered around the growth and characterization of GaAs, AlGaAs and their heterostructures.

This effort has led to the obtainment of high purity n-type GaAs (μ_n at 77 K in excess of 93,000 $cm^2/v\text{-}s$) an optimized As/Ga ratio of 72 and a substrate temperature of 650^oC. In addition, the effects of in-situ substrate etching and arsine cracking on high purity GaAs

were determined during this study. Low temperature photoluminescence data showing fine exciton structure at GaAs's band edge has been correlated with the growth parameters including substrate temperature and the As/Ga ratio. In addition, DLTS measurements indicate the dominant residual deep center, the electron trap EL2, decreases with lower As/Ga ratios. The traps' concentration has been reduced to less than $10^{13}cm^{-3}$ at As/Ga ratios less than 30. Finally, the behavior of the electron mobility, the carrier concentration and the photoluminescence efficiency for undoped GaAs films with the primary growth parameters has been determined. For example, under suitable growth conditions, thick (around 10 microns) semi-insulation GaAs layers may be reproducably obtained and incorporated buffer layers on semi-insulating substrates for a variety of device structures.

The growth of AlGaAs films has been investigated over the full range of alloy compositions with several As/(Ga+Al) ratios and over a temperature range from 550-800^{o}C. It was observed that the optical properties of these films were severely degraded due to the incorporation of oxygen from the growth ambient. In an effort to reduce oxygen contamination, a new oxygen gettering scheme was applied to the arsine gas, the suspected source of the contamination. The radiative yield of the $Al_{0.25}Ga_{0.75}As$ was improved by a factor of 5 as a result of the removal of moisture from the arsine gas. The use of this oxygen gettering system has resulted in narrow linewidths ($<$ 5 meV) in low temperature photoluminescence spectra of $Al_{.26}Ga_{.24}As$ film grown at relatively low temperatures (around 700^{o}C). However, the residual shallow impurities in AlGaAs films are at least two orders of magnitude greater than that of GaAs. It appears that the aluminum source, trimethyaluminum, needs further improvements in its purification to improve the AlGaAs quality. Improvement in the purity of OMVPE grown AlGaAs will have a direct impact on device structures incorporating AlGaAs semi-insulating buffers and selectively doped heterojunctions.

The heterojunction abruptness in GaAs/AlGaAs structures is critical to several device applications including modulation doped FET's and quantum well lasers. A series of layers have been grown over a broad range of substrate temperature incorporating quantum

well heterostructures as thin as 40 Å. It was observed that narrow quantum wells did not yield photoluminescence at the higher growth temperatures, apparently due to a substantial graded interface region between the GaAs and AlGaAs layers. Attempts to improve the heterojunction interface abruptness by stopping the growth at the heterojunction interface are currently underway.

The GaAs and AlGaAs films have been doped n-type using both hydrogen selenide and silane dopant sources, and p-type with the dopant source diethylzinc. It was observed that the selenium doping produces the longest minority carrier diffusion lengths as opposed to the silicon doping with silane. In addition, lower compensation has been obtained with selenium doping. The dopant memory effect commonly observed with the hydrogen selenide source was avoided by baking the reactor plumbing and reactor cell between growth experiments. The p-n junctions fabricated by OMVPE with these dopants exhibit large recombination currents under moderate forward bias relative to high quality LPE grown junctions due to a deep center whose origin has yet to be determined. As a result, for the OMVPE process to yield higher quality minority carrier devices, a solution to this problem is of prime importance.

DEGREES

None

PUBLICATIONS

1. "Carrier Compensation at Molecular Beam Epitaxy Interfaces", N.J. Kawai, C.E.C. Wood and L.F. Eastman, J. Appl. Phys., 53 (9) 6208-6213 (Sept. 1982).

2. "Investigation of Capless Heat Treatment of MBE n-GaAs", S.H. Xin, W.J. Schaff, C.E.C. Wood and L.F. Eastman, 1982 Int. Symp. on GaAs and Related Cpds, Albuquerque, NM (Sept. 19-21, 1982); Inst. Phys. Conf. Ser. 65 (5) 613-618 (1983).

3. "Characterization of High-Purity GaAs Grown by Low-Pressure OMVPE", J.R. Shealy, V.G. Kreismanis, D.K. Wagner, G.W. Wicks, W.J. Schaff, Z.Y. Xu, J.M. Ballantyne, L.F. Eastman and R. Griffiths, 1982 Int. Symp. on GaAs and Related Cpds, Albuquerque, NM (Sept. 19-21, 1982); Inst. Phys. Conf. Ser. 65 (2) 109-116 (1983).

4. "*Capped Versus Capless Heat Treatment of MBE n-GaAs*", S.H. Xin, W.J. Schaff, C.E.C. Wood and L.F. Eastman, Appl. Phys. Lett., 41 (8) 742-744 (Oct. 1982).

5. "Heat Treatment of Semi-Insulating Chromium-Doped Gallium Arsenide Substrates with Converted Surface Removed Prior to Molecular Beam Epitaxial Growth", S.C. Palmateer, W.J. Schaff, A. Guleska, C.E.C. Wood and L.F. Eastman, Appl. Phys. Lett., 42 (2) 183-185 (Jan. 1983).

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TASK 2 INVESTIGATION OF MICROWAVE FIELD-EFFECT TRANSISTOR PERFORMANCE LIMITS SET BY LAYER COMPOSITION AND CONTACT GEOMETRY

L.F. Eastman and D.W. Woodard

OBJECTIVE

The objective of this task is to investigate experimentally and analytically the performance limits of GaAs microwave power FET devices.

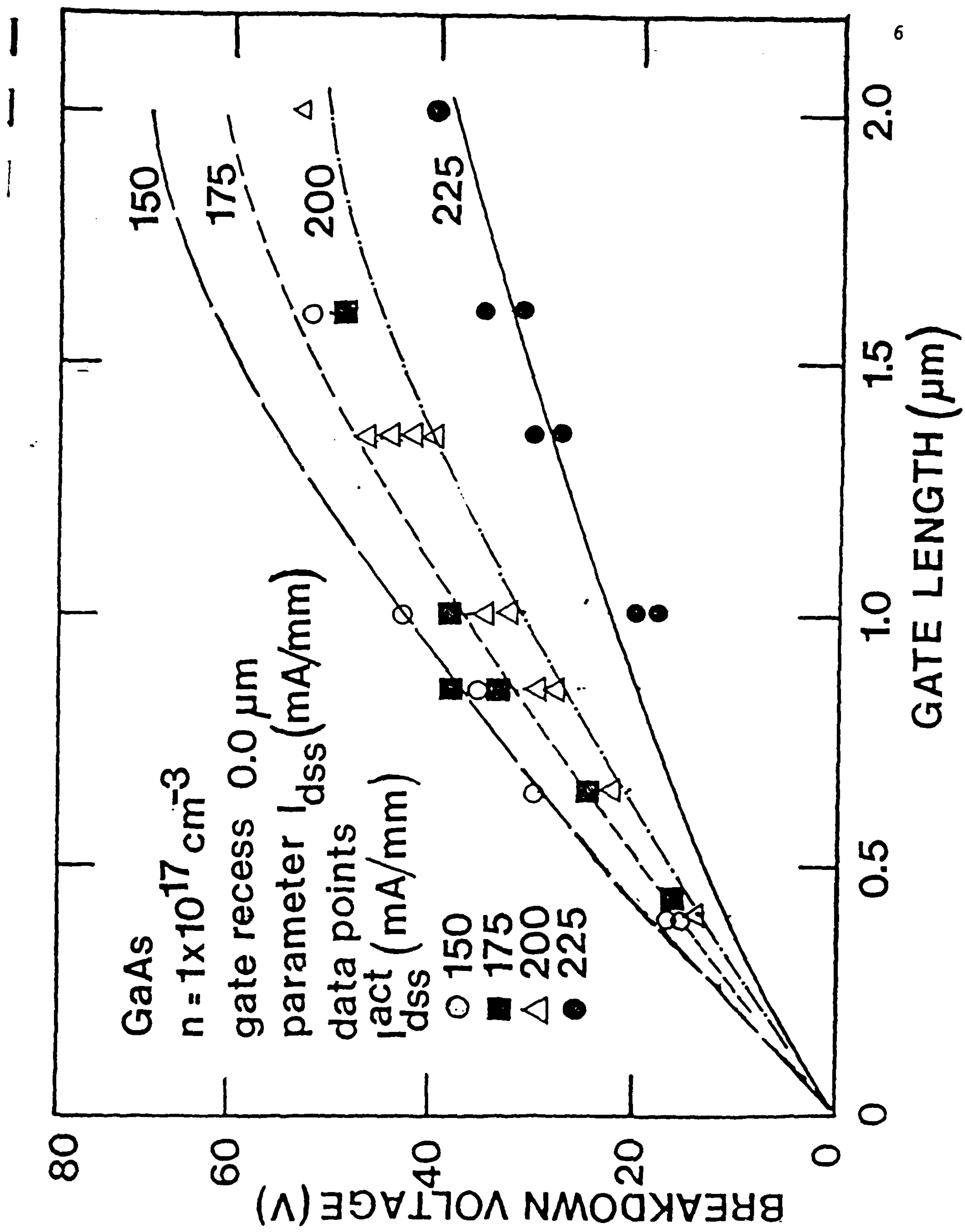
APPROACH

The approach taken has been to explore structural and materials related determinants of the breakdown voltage and output conductance. These determinents have included the surface notch configuration, electrode spacing, layer thickness and doping, source or type of expitaxial material, and buffer layer thickness, resistivity, and deep level occupancy.

PROGRESS

In the previous period, experimental and theoretical work showing an approximately linear dependence of breakdown voltage on gate length down to 0.8 microwave was reported. During the present period, these studies were extended down to 0.4 micron gate length. In addition, power limitations imposed by current flowing in the substrate were investigated. In an effort to control substrate current, a new type of buffer layer consisting of an AlGaAs-GaAs superlattice was employed. For this first attempt, parameters of the buffer layer were not sufficiently optimized to effect a reduction in the current. However, the device performance, for the first time on an AlGaAs buffer, was comparable to results with GaAs buffers. This suggests that the superlattice approach significantly improved the properties of the final AlGaAs layer under the GaAs active layer.

Figure 1 shows measured breakdown voltage as a function of gate length for devices with various zero bias saturation currents (I_{DSS}),



GaAs
n = 1x10^{17} cm^{-3}
gate recess 0.0 µm
parameter I_{dss} (mA/mm)
data points I_{dss}^{act} (mA/mm)
○ 150
■ 175
△ 200
● 225
150
175
200
225
0
0.5
1.0
1.5
2.0
GATE LENGTH (µm)
0
20
40
60
80
BREAKDOWN VOLTAGE (V)

Figure 1

and gate lengths down to 0.4 microns. It can be seen that the previously established trend of reduced breakdown voltage with reduced gate length continues down to only 15 volts at $L_g = 0.4$ microns.

At the same time that breakdown is decreasing with decreasing gate length, the substrate current is increasing, due to increased injection fields. Figure 2, which is based on an electrostatic model by P.H. Ladbrooke, shows that, for a 1/2 micron gate the effect of the substrate current is to reduce the expected power by about a factor of 2.

In an effort to reduce the substrate current, AlGaAs has been employed as a buffer layer at this laboratory as well as at others. In most cases this has successfully reduced the current, but only at the expense of greater noise or other problems. During this period, for the first time, devices have been made with AlGaAs buffer and microwave performance equal to that of ordinary GaAs buffered devices.[(1)] This was achieved by growing a GaAs-AlGaAs superlattice structure with 100 periods prior to growth of a 3 micron AlGaAs buffer layer.

The effect of the superlattice was to provide a large number of interfaces for trapping impurities and defects which diffuse from the substrate and tend to accumulate at interfaces. By the time the final AlGaAs buffer layer is grown the supply of such defects is exhausted by the deeper interfaces. Photoluminescence and DLTS measurements confirmed the reduced concentration of deep levels in the active layer. It is believed that further optimization of the parameters of the buffer layer will result in device performance exceeding that of GaAs buffer layers.

DEGREES

None

PUBLICATIONS

1. "Superlattice Buffers for GaAs Power MESFETs Grown by MBE", W.J. Schaff, L.F. Eastman, B. Van Rees and B. Liles, <u>5th MBE Workshop</u>, Atlanta, GA (Oct. 6-7, 1983); <u>J. Vac. Sci. Tech. B.</u> (1984).

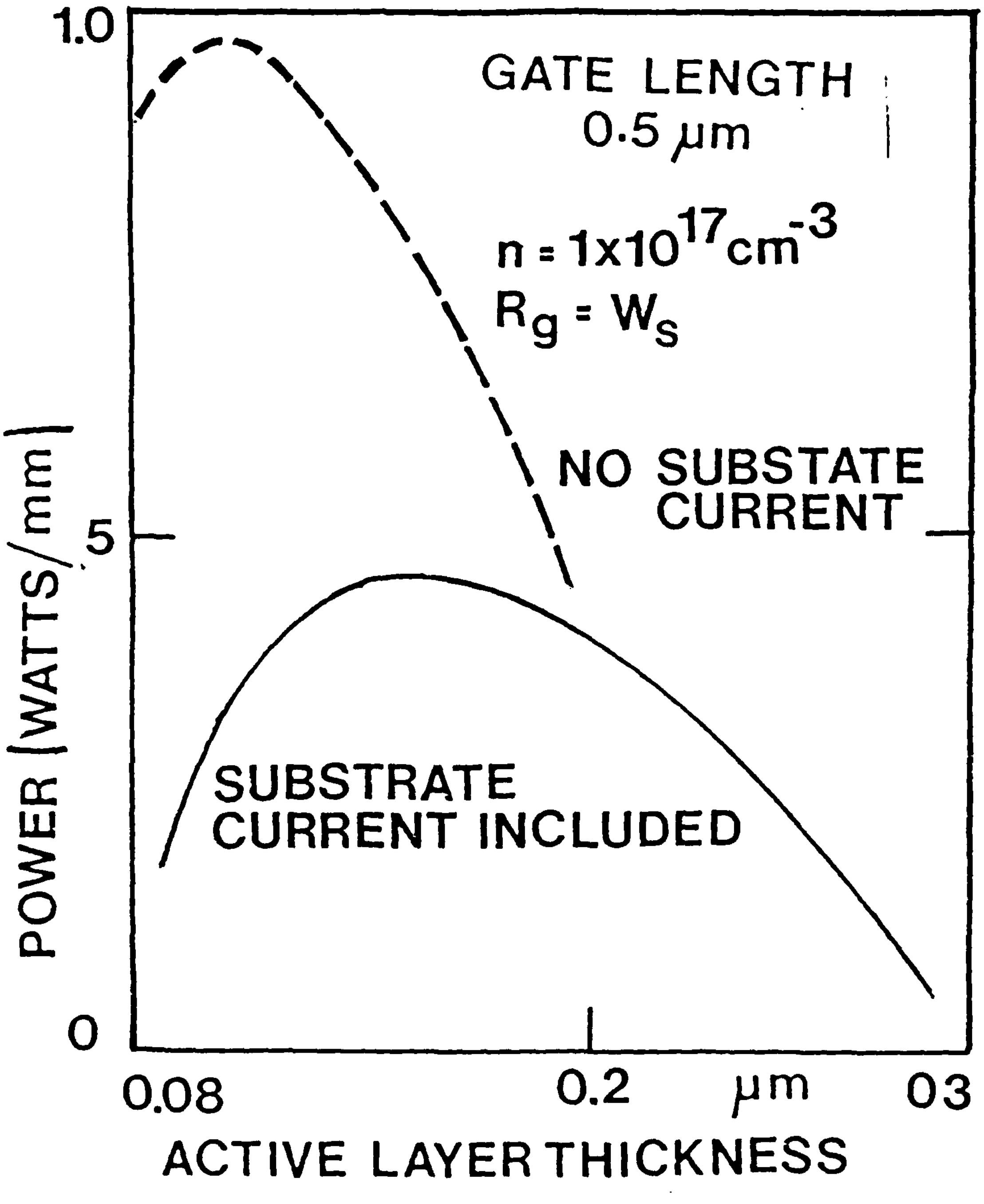

1.0
GATE LENGTH
0.5 μm
n = 1x10^17 cm^-3
Rg = Ws
NO SUBSTATE
CURRENT
.5
SUBSTRATE
CURRENT INCLUDED
0
0.08
0.2
μm
03
POWER (WATTS/mm)
ACTIVE LAYER THICKNESS

Figure 2

2. "The Large Signal Performance of GaAs MESFETS Fabricated from Material Grown by Molecular Beam Epitaxy", W.J. Schaff, L.F. Eastman, B. Van Rees adn B. Liles, Late Paper, Proc. Ninth Biennial High Speed Semiconductor Devices and Circuits Conf., Cornell University, Ithaca, NY (Aug. 15-17, 1983).

TASK 3 USE OF MBE TAILORED PROFILES FOR GaAs POWER FET's FOR IMPROVED PERFORMANCE

L.F. Eastman and G.W. Wicks

OBJECTIVE

A study of the behavior impurities and defects in MBE growth and their influence on electrical and optical properties of epitaxial films.

APPROACH

The majority of the effort of the past year of this project has been directed at substrate effects on MBE layers. Substrates were cleaved into two pieces, one of which was heated at 750°C in H_2 for 24 hours then repolished. MBE layers were grown simultaneously on both pieces and characterized.

Other areas which were investigated were Si incorporation into different orientations of GaAs during MBE growth, effects of interrupted growth on MBE films and annealing of MBE GaAs.

PROGRESS

Subjecting substrates to a bake and repolish cycle prior to epitaxy was conclusively shown to reduce impurity and defect outdiffusion from substrate to epitaxial layer. Secondary ion mass spectroscopy (SIMS) studies on MBE layers showed Mn accumulation at the substrate interface and Mn and Cr outdiffusion on unbaked substrates. These effects were not detected in layers grown on baked substrates. Deep level transient spectroscopy (DLTS) showed a reduction by a factor of 2 to 3 in the density of deep levels in MBE layers grown on baked substrates. Planar doped barriers (PDB's) grown on unbaked substrates exhibited barrier heights 10-20% lower than theoretically expected and poor uniformity. PDB's on baked substrates gave the expected barrier heights and excellent wafer uniformity. Finally, substrate baking plus precise control of arsenic to gallium ratio during MBE growth allowed the growth of single

quantum wells with the narrowest photoluminescence linewidths yet reported, 0.7 meV.

In other areas, silicon was found to be weakly amphoteric on (100) surfaces of GaAs in MBE giving n-type films, but strongly amphoteric on (110) surfaces giving p-type films above 550°C and n-type films below 550°C.

Carrier depletion in n-type MBE films was found to be 2-8 x $10^{11}cm^{-2}$ at interrupted growth interfaces when the layer was exposed to air or atmospheric pressure of nitrogen. No depletion was observed at interfaces which were maintained in an As_4 overpressure while the growth was stopped.

Finally, MBE GaAs layers which were capped with Si_3N_4 and annealed at 700°C were found to have enhanced defect exciton and carbon acceptor features in their photoluminescence and enhanced EL2 levels as seen by DLTS. No such enhancement was observed in layers which were annealed without a cap in arsenic overpressure.

DEGREES

S. Palmateer, M.S., August 1982

W. Beard, M.S., January 1983

J. Ballingall, Ph.D., May 1982

PUBLICATIONS

1. "Carrier Compensation at Interfaces Formed by Molecular Beam Epitaxy", N.J. Kawai, C.E.C. Wood and L.F. Eastman, J. Appl. Phys., 53 (9) 6208-6213 (Sept. 1982).

2. "Capped Versus Capless Heat Treatment of Molecular Beam Epitaxial GaAs", S.H. Xin, W.J. Schaff, C.E.C. Wood and L.F. Eastman, Appl. Phys. Lett., 41 (8) 742-744 (Oct. 1982).

3. "A Study of Substrate Effects on Planar Doped Structures in Gallium Arsenide Grown by Molecular Beam Epitaxy", S.C. Palmateer, P.A. Maki, M.A. Hollis, L.F. Eastman, C. Hitzman and I. Ward, presented at Int. Symp. GaAs and Related Cpds, Albuquerque (Sept. 1982); Inst. Phys. Conf. Ser. No. 65; Chapter 3, 149-156 (1983).

4. "Heat Treatment of Semi-Insulating Chromium-Doped Gallium Arsenide Substrates with Converted Surface Removed Prior to Molecular Beam Epitaxial Growth", S.C. Palmateer, W.J. Schaff, A. Galuska, J.D. Berry and L.F. Eastman, Appl. Phys. Lett., 42 (2) 183-185 (Jan. 1983).

5. "Effect of Substrate Annealing and V:III Flux Ratio on the Molecular Beam Epitaxial Growth of AlGaAs-GaAs Single Quantum Wells", P.A. Maki, S.C. Palmateer, G.W. Wicks, L.F. Eastman and A.R. Calawa, J. Electronic Materials, 12 (6) 1051-1063 (Nov. 1983).

TASK 4 MBE MULTIPLE GaAs-$Al_xGa_{1-x}As$ HETEROJUNCTIONS FOR CONFINEMENT OF ELECTRONS FOR IMPROVED FET PERFORMANCE

L.F. Eastman and G.W. Wicks

OBJECTIVE

The objective is to utilize the GaAs-AlGaAs heterojunction for improved FET structures.

APPROACH AND PROGRESS

Results

1. GaAs/AlGaAs Superlattice Buffers for FET's

Photoluminescence (PL), secondary ion mass spectrometry (SIMS), deep level transient spectroscopy (DLTS) and microwave FET performance have consistently demonstrated the superiority of GaAs/AlGaAs superlattice buffers over conventional GaAs or AlGaAs buffers. The interfaces of the superlattice have demonstrated the ability to getter impurities and defects such as ion and the deep level, EL2. The following data was obtained at 10 GHz on FET's fabricated on MBE grown material (no data is given to AlGaAs buffers since they exhibited extremely poor microwave performance):

buffer layer	superlattice buffer	GaAs buffer
	(270Å $Al_{.45}Ga_{.55}As$/30Å GaAs,x100)	3 microns
saturated output power (watts/mm)	.71	.63
power added efficiency	.31	.27

2. Annealing Characteristics of Modulation Doped Structures

In order to construct short gate, ion implanted self aligned modulation doped FET's, the high electron mobilities in such structures must not be seriously degraded upon annealing. Previous to this work, little success had been achieved in this area. In this

work, the ability of the modulation doped structure to maintain its high electron mobility during annealing was found to depend on the spacer layer thickness and the sheet concentration of electrons in the two dimensional electron gas. Apparently the electric field in the spacer layer causes the donors to drift during the anneal from the AlGaAs into the spacer layer toward the two dimensional electron gas, which causes a degradation in electron mobility. This effect is lessened by reducing the sheet concentration, thereby lowering the electric field, or by widening the spacer layer, thereby increasing the distance that the donors must move before degraded electron mobility occurs. These two effects are demonstrated in the following data on modulation doped samples annealed at 800°C for 15 minutes (a typical annealing cycle for activating silicon implants into GaAs):

	μ_{77} before anneal	μ_{77} after anneal
$n_s = 5 \times 10^{11} cm^{-2}$ spacer - 100 Å	100,000 cm^2/v-sec	90,000 cm^2/v-sec
$n_s = 1.2 \times 10^{12} cm^{-2}$ spacer - 75 Å	62,000 cm^2/v-sec	2,300 cm^2/v-sec

3. Modulation Doped Single Quantum Wells

Enhanced mobilities have been achieved in modulation doped single quantum wells. Single quantum wells 120 Å wide were grown on 0.5 micron $Al_{.3}Ga_{.7}As$ buffer layers. On top of the quantum well was an undoped AlGaAs spacer layer and a doped AlGaAs layer. At sheet electron concentrations of $5 \times 10^{11} cm^{-2}$, room temperature mobilities of 7000 cm^2/v-sec and 77 K mobilities of 7800 cm^2/v-sec were obtained. This structure is applicable to high speed logic and medium power FET's. It has the advantages of high electron mobility and reduced saturation velocity in the AlGaAs buffer.

DEGREES

None

PUBLICATIONS

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3. "The Large Signal Performance of GaAs MESFETS Fabricated from Material Grown by Molecular Beam Epitaxy", W.J. Schaff, L.F. Eastman, B. Van Rees and B. Liles, 1983 IEEE Cornell Conf. on High Speed Semiconductor Devices and Circuits, Ithaca, NY (Aug. 1983).

TASK 5 HIGH SPEED RECEIVERS FOR OPTICAL COMMUNICATIONS

J. Ballantyne and D.K. Wagner

OBJECTIVE AND APPROACH

High Speed Detectors and Receivers

Previously, several different types of photoconductive detectors (OPFETS) were monolithically integrated with a GaAs MESFET amplifier. Although individual photoconductors and transistors performed well, significant problems were encountered in the biasing of the amplifier, overall circuit yield, and longer than expected decay times when excited by picosecond optical pulses. Bypassing circuit nodes effectively at GHz frequencies and the reliability of a large number of ultrasonically bonded wires required for the circuit (9) were also problems. Together, these problems prevented high speed testing of the complete receiver.

Many of the above are processing or design flaws, not fundamental problems. Several are interconnected. The level shifting biasing scheme attempted was thought to be the simplest. However, it necessitated the large number of ultrasonic bonds, as well as having the initial power transients cause severe circuit trauma before the different bias voltages to the stages stabilized. This often caused the forward biasing of the MESFET gates, damaging the transistors.

Our solution is a redesign that uses at the most a positive and negative supply and includes either Schottky diode strings to perform the necessary DC voltage level shifts internally, or a differential amplifier scheme with zero DC offset from input to output stage. The feasibility of differential amplifier schemes in particular and self-biasing schemes in general depends on the uniformity and quality of the epitaxial layers the circuits are fabricated in. The characteristics of the transistors for differential pairs have to be very closely matched. Otherwise, the zero DC offset property is not obtained. The current layer quality indicates that a self-biasing scheme with level shifting diodes is the most practical, unless more uniform layers can be obtained from the MOCVD system or other

sources. With any self-biasing scheme, there are less circuit nodes to bypass. Also, improved capacitors have been obtained for the circuit bypassing. They are smaller in physical size and have higher self-resonant frequencies and better loss tangents, thus the bypassing problem should be alleviated.

Difficulties with circuit yield are now less important due to an improved photolithography system being used and better quality layers being used for processing.

The most potentially serious problem is the long decay time observed in optical impulse (3 ps FWHM) is fast in all cases (less than 100 ps), the response has a long tail. This decay may be caused either by circuit effects (bonding wire inductance, device capacitance, bias tee insertion loss, etc.) or excess minority carriers being trapped in the semi-insulating substrate.

A GaAs/AlGaAs heterostructure was grown on the MOCVD system. The undoped AlGaAs layer acts as a barrier to prevent the excess minority carriers (holes), which determine the decay characteristics of the device, from entering the substrate and becoming trapped. The AlGaAs has a larger band gap (1.9 eV) than the GaAs (1.43 eV), creating the barrier. As a further precaution, a thicker layer of GaAs was grown (.6 micron) than had been used in previous work (.3 micron). Since the absorption coefficient in GaAs is .25 micron at the wavelength used in our tests, about 90% of the light is absorbed in the epilayer.

Various interdigitated photoconductors were fabricated ranging in size from 5x5 to 400x400 microns. All but the smallest devices are suitable for direct coupling of optical fibers to the surface. I-V measurements are consistent with previous detector characteristics if changes in active device area are noted. The largest devices (400x400) were not successful because of material inhomogeneties. A problem with all larger area arrays is the relatively large amount of current needed (up to 100 mA). This also leads to undesirable heating effects in the devices. Work is in progress on a normally off detector which would have a low quiescent current. Such a device would eliminate both of the above undesirable effects.

For high speed pulse measurements, a new mount was devised by modifying an SMA microwave connector suitably so that the devices are mounted directly on the connector. Optical impulse measurements show a long tail still present in the new detectors, although reduced from previous levels by a factor of 30%. The device decay now is exponential. Previously, the decays were more anomalous, possibly due to reflections from the old test mount. The continuing long decays may be due to surface recombination effects, or continued hole trapping at the lower interface. Improved layer structures are being designed to study the problem. The pulse response has been found to depend on the device bias and the illumination levels employed in the tests, as well as device active area. These effects are being studied to determine the optimum size and operating conditions. The fastest responses have a FWHM of 100 ps at 3 V bias at .1 mw incident power (25x25 micron device).

PROGRESS

MOCVD Growth of Detector Layers

For the past two years we have been assembling a system for the MOCVD (Metal-organic chemical vapor deposition) growth of III-V compounds. This year the machine produced GaAs and AlGaAs layers equal to or better than the best grown anywhere else. Undoped layers have shown liquid nitrogen mobilities in excess of 90,000 and sharp photoluminescence structure seldom seen in other laboratories. The photoluminescence spectra obtained on the AlGaAs material is the best in the published literature. In and P sources have been installed in the machine and layers of GaInAs have been successfully grown. However, much work remains to be done to get good growth rates for high quality GaInAsP layers across the entire composition range at low pressures. Materials grown in this machine are now being used in all of our other opto-electronics program. Both N and P type layers can be produced in the system, and the unique system design which allows in situ cleaning has allowed growth of layers with no perceptible memory effect from one run to the next.

DEGREES

None

PUBLICATIONS

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TASK 6 DYNAMIC AND SPECTRAL CHARACTERISTICS OF SEMICONDUCTOR LASER MATERIALS AND STRUCTURES

C.L. Tang

OBJECTIVE, APPROACH AND PROGRESS

I. Femtosecond relaxation of photoexcited nonequilibrium carriers in AlGaAs (Ref. 1) - The ultimate speed of semiconductor electronic and optic devices depends upon the relaxation time of hot electrons over submicron distances in semiconductors. To determine these characteristic times, subpicosecond time resolution is needed. Using the recently developed femtosecond lasers and measurement techniques, we have measured for the first time the femtosecond intraband relaxation time of nonequilibrium carriers in the conduction band of a semiconductor. Optical saturation of highly excited states in the conduction band of a semiconductor and the subsequent extremely fast energy relaxation due to carrier-carrier and optical phonon scattering at room temperature are observed. The corresponding measured lifetime for states 160 meV above the band edge in $Al_{(0.34)}Ga_{(0.66)}As$ is in the range of 80 to 30 femtoseconds depending upon the photoexcited carrier ensity. Work is proceeding on other semiconductors.

II. Nonlinear luminescence and time-resolved diffusion profiles of photoexcited carriers in semiconductors (Ref. 2) - A new and general optical technique has been developed for studying carrier dynamics in semiconductors which is based upon the luminescence nonlinearity resulting from the bimolecular recombination of the carriers. The technique has been used to obtain time-resolved diffusion profiles and the hole mobility in photoexcited GaAs.

III. Photoluminescence measurements of Zn-doped AlGaAs grown by metalorganic chemical vapor deposition (Ref. 3) - We have investigated the photoluminescence properties of Zn-doped GaAlAs

grown by metalorganic chemical vapor deposition (MOCVD). The photoluminescence spectra exhibit weak bound exciton lines, donor-acceptor pair transitions, free-to-bound excitons, and low energy broad bands. The Zn acceptor ionization energy is determined from the free-to-bound transitions as a function of aluminium concentration x up to 0.46. Two low energy bands have been observed in Zn-doped $Ga_{(1-x)}Al_{(x)}As$. One is at 1.65 eV and is identified as due to the Zn(Ga)-V(As) complex. Another band has been observed at 1.81 eV from samples with x near or beyond the cross-over. It is well separated from the band edge, but its origin is not yet well understood.

VI. Time-wavelength multiplexing of mode-locked external-cavity semiconductor lasers (Ref. 4) - A technique for obtaining multicolor operation of mode-locked lasers has been applied to an external-cavity semiconductor laser. The generation of two perfectly synchronized optical pulse trains of different wavelengths from such a laser is demonstrated.

V. Photoluminescence of GaAs-AlGaAs multiple quantum well structure under high excitations (Ref. 5) - Allowed transitions between the n = 1, 2, and 3 sub-bands of a multple quantum well heterostructure of GaAs/AlGaAs are seen in spontaneous emission under high excitations. The observed peaks agree very well with the calculated locations of the peaks when the finite depth of the potential well and the nonparabolicity of the conduction band are taken into account. The basic features are seen under cw or picosecond pulse excitation and at room temperature, 77 K, or 4.2 K.

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TASK 7 CARRIER DYNAMICS IN COMPOUND SEMICONDUCTORS STUDIED WITH PICOSECOND OPTICAL EXCITATION

G.J. Wolga

OBJECTIVE

We have two principal objectives. The first is to study hot electron/hole energy loss processes in GaAs and other compound semiconductors. We wish to elucidate the dynamics of electron energy relaxation when excitation is sufficient to permit electron scattering into the conduction band upper valley from relaxation lower in the conduction band, including energy states close to the conduction band minimum. Hot carriers are produced by photo-excitation with the shortest possible tunable optical pulses. To accomplish this, techniques for generating optical pulses with duration shorter than the currently available 1.5 picoseconds are being investigated. The second is to develop and apply techniques for picosecond electronic measurement of the performance of ultra-fast electronic devices including detectors and transistors.

APPROACH

Limitations on ultra-high speed electronic device performance ultimately arise from hot carrier relaxation and scattering processes. We are photo-exciting electron-hole pairs in GaAs with pairs of 1.5 picosecond optical pulses. A selectable time delay (0 - several nanoseconds) between the pulses permits the inference of carrier relaxation from the variation of photoluminescence from the pair of pulses with time delay.(1,2,3) The excitation energy of the charge carriers is a second important parameter. By frequency tuning our optical pulses, we can excite carriers to various energy regions of the conduction band, e.g.: near the band minimum; to energy states near the upper valley where scattering of carriers into the upper valley takes place; to intermediate states. We wish to perform the measurements with the shortest possible pulses so that the temporal response observed is essentially indicative of the hot

carrier dynamics. At present, the shortest optical pulses obtainable (1.5 picosecond) in the 700-800 nm range are generated by synchronously mode-locked dye laser pulses pumped by actively mode-locked Kr^+ ion laser pulses. To generate shorter optical pulses, we must employ the passively mode-locked, colliding pulse techniques pioneered in the shorter wavelength regions.[4] Unfortunately, the saturable absorbers required for sub-picosecond pulse generation in the infrared have not been identified and tested. We are therefore measuring the optical saturation properties of suitable absorbers in the near infrared. Successful identification of saturable absorbers with sufficiently fast relaxation will permit us to generate and employ sub-picosecond optical pulses in our measurements.

Picosecond electronic measurements on electronic devices are based on ultra-fast photoconductors imbedded in micro-stripline circuits.[5] We are developing such detectors using photolithographic techniques to deposit the transmission lines and radiation (ion) damaged semiconductors to obtain photoconductors with sufficiently fast charge carrier relaxation. We are also developing electronic pulse correlation techniques[5] using pairs of photoconductors as charge generators and sampling gates to measure ultra-short electronic pulse propagation on the stripline circuits. These techniques must be extended to permit coupling to electronic devices for measurement of their properties at extremely high frequencies.

PROGRESS

A. Hot Carrier Relaxation in GaAs

Since the start of the present reporting period we have completed the apparatus for pump-probe luminescence studies. We have fabricated a double monochromator from two identical 1/4-meter monochromators that provides excellent tracking and off resonance rejection performance. A versatile digitally controlled stepper-motor drive system for the monochromator was designed and fabricated. We are using an S-20 photomultiplier that has good quantum efficiency and relatively low dark current in the 700-800 nm region. We have

reworked the sample section of a low temperature optical dewar to permit both reflection and transmission studies to be carried out at 77 K or lower if we pump on the liquid N_2. Strong photoluminescence was measured in reflection from a GaAs in an AlGaAs:GaAs:AlGaAs sample that was immediately available. We are currently fabricating sufficiently thin GaAs samples so that we can commence both reflection and transmission (absorption studies). The photoluminescence from GaAs showed a long wavelength luminescent tail indicating production and observation of hot electrons excited by our 700 nm pulses. The apparatus for generating pump-probe pulses separated by variable time delay is operating.

B. Sub-Picosecond Laser Development

We have set up a pump-probe absorption experiment to study the relaxation behavior of saturable absorber dyes suitable for mode locking near-infrared dye lasers. In early work with cryptocyanine dissolved in ethyline glycol or propanol we discovered that a non flowing sample displayed thermal blooming effects with very long relaxation times. We therefore set up a flowing dye-jet as the sample to bypass these effects. We are currently studying cryptocyanine with the pump-probe absorption technique. Cryptocyanine has successfully mode locked ruby lasers in the 694 nm region and was studied by Sooy et al.[6] who inferred a relaxation time < 5 nsec. With our much better temporal resolution, we shall extend their measurements to determine the relaxation time of cryptocyanine in various solvents and to see whether this dye will recover from saturation sufficiently rapidly to operate a colliding-pulse ring dye laser.

C. Picosecond Electronics

We have acquired the techniques for fabricating micro-striplines on semiconducting substrates. We developed and tested a test fixture for our photoconductive charge generators that operates at 18 GHz (8.8 picoseconds). We have built and studied fast, photoconductive detectors (charge generators in the micro-stripline geometry) on two

different substrate materials. Both 3 micron and 5 micron gap geometries have been tested.

1. InP: These devices were made on semi-insulating (iron doped) material. They exhibited responses no faster than 100 picoseconds, thus too slow for our purpose. However their sensitivity was excellent as we obtained 40 mV signals into matched 50 ohm loads with 5 volt bias.

2. Radiation Damaged Silicon-on-Sapphire (SOS): The SOS substrates were radiation damaged with varying doses of O^+ ions. Our best detectors have given 10 picosecond response (deconvolved from 30-35 picosecond pulses observed with our sampling scope). Sensitivity is lower than with InP as we obtain 5 mV pulses with 40 volt bias. We are currently improving the ohmic contact of the stripline to the silicon by varying the stripline material and fabrication procedure. We anticipate obtaining performance near 1 picosecond with suitable treated aluminum micro-striplines. These detectors are routinely used for optimizing laser performance and provide sufficient sensitivity to monitor 2 picosecond dye laser pulses with 50 mW average power. Our early attempts to combine two photoconductive detectors in a correlation configuration were thwarted by poor ohmic contact of the micro-striplines.

DEGREES

NONE

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PUBLICATIONS

None

TASK 8 ADVANCED DESIGN TECHNIQUES FOR MICROWAVE GaAs FET AMPLIFIERS

W.H. Ku

OBJECTIVE

The primary objectives of this continuing research program are to derive fundamental device/circuit performance limitations for GaAs metal-semiconductor FETs (MESFETs) and to develop advanced and integrated analytical and computer-aided design (CAD) techniques for the synthesis and design of GaAs amplifiers leading to monolithic microwave integrated circuits (MMICs) and subsystems. A secondary objective of this research program is to fabricate prototype GaAs MESFET amplifiers and circuits in microstrip and monolithic realizations using state-of-the-art submicron gate-length MESFETs to verify the integrated design approach developed in the main portion of this 6.1 JSEP program.

It is anticipated that, because of the fundamental nature of this proposed research, the results obtained should have a direct and significant impact on various DOD programs involving ultra-wideband GaAs MESFET amplifiers which are directed to ECM and EW system applications and monolithic transceiver modules for phased array applications.

APPROACH

Tremendous progress has been made over the past several years in low-noise and power GaAs MESFET devices and integrated circuits. Low-noise GaAs MESFETs with submicron gate lengths using optical and e-beam lithography have been reported which can operate at frequencies up to 60 GHz. Power GaAs FETs are capable of output powers of hundreds of milliwatts at K-band. More significantly, recent advances in monolithic integration of GaAs integrated circuits (ICs) have stimulated great interest in the applications of GaAs ICs for both analog and digital systems.

It is expected that with the advent of monolithic realizations, the complexity of the device and circuit design for GaAs ICs will increase significantly. Techniques common to the design of silicon ICs must be developed for GaAs ICs. As defined in the previous proposal, we plan to use an integrated approach involving both analytical and computer-aided design and synthesis techniques for the design of monolithic GaAs ICs. New and innovative circuit designs including feedback and distributed amplifiers will be studied. Nonlinear circuit analysis programs will be developed for monolithic GaAs MESFET devices and circuits. An integral part of our technical approach is to verify our designs by the design and actual fabrication of prototype monolithic GaAs MESFET circuits.

PROGRESS

Significant progress on this unit of the research program was made on the successful design and fabrication of state-of-the-art submicron gate-length GaAs MESFETs and broadband monolithic medium-power GaAs MESFET amplifiers. In addition, new analytical and computer-aided design techniques have been developed for monolithic GaAs MESFET feedback amplifiers, distributed amplifiers and mixers. A new computer-aided synthesis technique applicable to odd-order lumped and distributed matching networks has also been successfully developed. This work has resulted in a number of publications, conference presentations and two patent disclosures.[1-15]

Results we have obtained on sub-half-micron GaAs MESFETs are comparable to the best achieved in any laboratory and our successful fabrication of monolithic medium-power amplifiers is a first in any university. Progress of our research is summarized in the following subsections.

a) Design and Fabrication of Submicron Gate-Length GaAs MESFETs

Fabrication technology for extremely-short gate length GaAs single- and dual-gate MESFETs has been developed to minimize parasitic resistances. Based on the developed technology, a DC transconductance of 360 mS/mm gate width was observed in a GaAs FET.

Three optical lithographic techniques have also been developed to produce state-of-the-art sub-quarter-micron gate structures. 0.2 micron long Cr/Au gates with thickness of 0.9 micron have been successfully fabricated by using the first technique, which we call the pile-up masking technique.(9) These gate structures are superior to the state-of-the-art gates fabricated by electron beam.

Gate lengths were further minimized to 0.1 micron with an aspect ratio (gate thickness/gate length) of approximately 20 by employing the second gate technique which we call the gate-wall technique.(6)(7) Using this high aspect-ratio gate structure, GaAs MESFETs have been fabricated with gate lengths as short as 0.1 micron and widths as wide as 300 micron. Electrical properties of GaAs FETs with long and ultra-short gate lengths fabricated by this technique were experimentally compared for the first time.(8) The gate length effect on the FET transconductance, pinchoff voltage, drain current, output conductance and knee voltage were evaluated.

A new fabrication technique has been developed to generate sub-half-micron T-shaped (or mushroom) gates in GaAs MESFETs.(12) The technique uses a single-level resist and an angle evaporation process. (A patent disclosure on this new technique has been filed). By using this technique, T-shaped gates with lengths as short as 0.2 micron near the Schottky interface have been fabricated. Measured gate resistance from this structure was 6.1 ohmic/mm gate width which is the lowest value ever reported for gates of equal length. GaAs single- and dual-gate MESFETs with 0.3 micron long T-shaped gates have been fabricated. At 18 GHz, maximum available gain of 9.5 dB in the single-gate FET and maximum stable gain of 19.5 dB in the dual-gate device have been measured.(12)

b) Design and Fabrication of Broadband GaAs Monolithic Microwave Power Amplifiers

A broadband 6-12 GHz medium-power GaAs monolithic power amplifier has been successfully designed, fabricated and tested based on the work of this research unit. This represents the first successful MMIC realization of GaAs MESFET amplifiers in any

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university of the U.S. and abroad. We obtained 165 mW of outp power with 5 dB of power gain across the octave frequency band of (12 GHz. The submicron GaAs FET used has 500 micron total ga periphery and was fabricated using the angle evaporation techniq described previously. A combined computer-aided synthesis and larg signal dynamic characterization technique was used in the design (the broadband monolithic power amplifier.

c) Computer-Aided Synthesis for MMICs

Computer-aided synthesis of lumped and distributed element eve order amplifier matching networks developed by Ku and Petersen h been extended to include odd-order networks.(14) The gain-bandwid performance of general odd-order networks as well as that of sever specific odd-order topologies have been evaluated explicitly. Tabl of circuit element values for a number of lumped and distribut element topologies for narrow and wide bandwidths have been obtaine These results provide general design information for monolith microwave GaAs MESFET amplifiers and represent a further advance i the computer-aided design and synthesis of monolithic microwa integrated circuits (MMICs). Results are presented in a Ph.I dissertation by Air Force Catain Jerry Dijak, entitled "Compute Aided Synthesis and Design of Monolithic Microwave GaAs MESF Amplifiers".

d) Design of Monolithic GaAs MESFET Distributed Amplifiers

We have recently developed a new and general design theory f monolithic GaAs MESFET distributed amplifiers. Preliminary resul of this design theory have been presented recently(14) and a mo complete paper was presented at the IEEE/Cornell Conference on Hi Speed Semiconductor Devices and Circuits in August 1983.(1 Monolithic distributed GaAs FET amplifiers have been reported in t literature but the designs are based on a number of simplify assumptions which restrict their general applicability. The des theory we have developed is more general and is applicable to b lumped and distributed gate and drain matching elemen

Based on measured 0.5 micron and 0.25 micron GaAs MESFET characteristics, the predicted distributed amplifier responses extend from 2 GHz to 26 GHz and 40 GHz, respectively.

e) Computer-Aided Simulation and Design of Microwave MESFET Mixers

We have developed a nonlinear MESFET circuits modeling and analysis computer program based on state variables formulation and fast convergent time-domain analysis. This new computer program has been used for the computer-aided simulation and design of microwave GaAs MESFET mixers. Mixers considered include single ended single- and dual-gate FET mixers and balanced mixers. This program fills a void in the area of computer-aided design of microwave mixers using GaAs MESFETs.

DEGREES

None

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TASK 9 WIDE BAND CIRCUITS AND SYSTEMS

H.J. Carlin

OBJECTIVE

The broad aim of this research program is to apply the wealth of circuit theoretic ideas to the solution of design problems associated with high frequency devices, structures and systems. Of particular interest are two topics: 1) The design of microwave and higher frequency broadband amplifiers. 2) Dispersion in dielectric waveguides particularly those guides applicable to propagation of optical signals.

APPROACH

The fundamental concept that underlies this program is to exploit the variety of sophisticated network theoretic methods to the solution of design problems at high frequencies where, generally speaking, distributed parameter circuits are employed. Thus in one phase of our research we have used the procedures of gain-bandwidth circuit theory coupled to new Computer Aided Design (CAD) methods to achieve a whole new practical approach to broadband FET amplifier designs. In another phase of the research we have used the theory of distributed parameter networks to obtain equivalent circuits for dielectric waveguide. This theory in turn leads to a simplified analysis and understanding of optical guide having a variable dielectric constant with respect to transverse dimensions.

Our approach is then to continue to utilize the insights and techniques obtained from circuit theoretic methods by applying them to high frequency devices and propagating structures.

If one examines the general literature of high frequency engineering one cannot but be impressed with the wide use of circuit methods in non-obvious contexts where conventional low frequency models are not applicable. Modeling, high frequency equalization, propagation analysis of waveguide, circuit descriptions of physical phenomena (e.g., Hall effect by non-reciprocal circuits), filtering

and other forms of signal processing are just a few examples of the variety of topics where circuit methods are now extensively employed.

Under this research task for instance, a great deal of use has been made of the circuit theory of broadband matching. This is a sophisticated branch of network theory which underlies the design of structures and systems which must operate into complex loads or even multiports. Using the guiding principles of this theory and coupling these fundamentals to numerical methods, we have developed our own CAD programs for the design of multistage FET amplifiers.

As another aspect of the background of this program, consider first the pioneering work of Dicke and Purcell at the Radiation Laboratory in applying circuit ideas, generally via the scattering matrix, to problems of conducting wall waveguide propagation. In our work many of these ideas have been used and generalized to give a circuit treatment of propagation in non-walled dielectric waveguide including a novel use of transverse resonance equivalent circuits for the treatment of dispersion in graded index optical guide.

The references to be found listed at the end of this task description give a variety of papers we have contributed to the technical literature that provide a broad background for our proposed continued effort in utilizing network methods for high frequency applications.

PROGRESS

We consider as a major contribution of our research under this program a group of technical papers[1][2][3][4][5] which detail a new approach to the design of broadband circuits and systems. In this group of references we describe a novel CAD design procedure "The Real Frequency Method" which has been used for wideband (especially FET) multistage amplifiers. We show in these papers that in fact this new CAD method leads to designs which are superior to those stemming directly from analytic gain-bandwidth theory, though the latter theory still provides the basic principles upon which all broadband matching methods must be based. Indeed we consider reference (4) on "Double Matching" a breakthrough in the art of broadband circuit design.

It appears that the techniques laid down in these papers are being widely disseminated in industry. For example, recently at the Boston IEEE-MTT Symposium (May 31, 1983) Dr. Siddik Yarman (who received his Ph.D. under this program) assisted by Prof. H. J. Carlin (PI) organized a *Workshop on Broadband Matching* based on our research. That workshop proved to be one of the most popular sessions at the MTT Conference. Our most recent papers[4][5] give a new and simplified analytic theory of "Double Matching" (load and source terminations both complex) as well as an implementation of the CAD Real Frequency Technique for designing wideband microwave FET amplifier interstages and these topics elicited a great deal of interest at the Workshop.

The other aspect of our research progress concerns circuit applications to propagation in dielectric waveguide. In earlier work[6][7][8] we have applied network methods to obtaining circuit models for dielectric loaded conducting walled guide, including microstrip. We have also published models for open dielectric waveguide.[9] Mr. Henry Zmuda in his Doctoral research has now been applying these ideas using transverse resonance circuit models for treating propagation problems in graded index dielectric rod waveguide. The procedure uses what is in effect a novel stepped uniform guide model for establishing a CAD method of dispersion analysis for longitudinally uniform dielectric waveguides which have rather complicated nonuniform transverse configurations. Initial numerical results look very promising.

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H. Zmuda, M.S., June 1982

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TASK 10 GALLIUM ARSENIDE BALLISTIC ELECTRON TRANSISTORS

L.F. Eastman, D.W. Woodard and G.W. Wicks

ABSTRACT

This task involved research on obtaining and applying high electron velocity in GaAs for ultimate use in high frequency transistors. The ballistic limit of electron velocity, where the electron kinetic energy equals the potential drop experienced by the electron, was sought. Conditions for obtaining such highest allowable velocity were studied and are explained in this report. Ultra-short field effect transistors in both the usual, horizontal and the vertical configuration were studied experimentally. Horizontal FET devices with gate lengths down to .3 microns were studied, and vertical FET's with .15 microns gate length were studied. In addition, the use of heterojunctions to launch ballistic electron into short vertical drift regions in both the field effect transistor and the bipolar transistor was initiated. The benefits and problems of these configurations are covered in this report.

I. INTRODUCTION

In order to obtain high frequency transistors, the highest possible electron velocity is necessary to make a short transit time. Work initiated by the author and his associates four to five years ago at Cornell, led to the concept of obtainable ballistic electron velocity limits in GaAs. In this limit the electrons accelerated through a short drift space have kinetic energy equal to the potential drop the electron has experienced. The maximum electron velocity in GaAs in the (100) crystal direction is limited to 9.5×10^7 cm/s. For the case of gradual acceleration, through a lightly doped region .4 microns long, average electron velocity of about 4×10^7 cm/s can be obtained. This value is just under the 4.75×10^7 cm/s average expected for a linear rise of electron velocity with time, showing modest effects of collisions. For the case of impulse acceleration and drift in an electric field of about 2,000 V/cm, through a lightly doped region .6 micron long, an average electron

velocity of about 8 x 10^7cm/s is possible for about .25 eV electron injection energy. This value is below the 8.5-9.0 x 10^7cm/s electron velocity at this energy, due to modest effects of collisions. In both cases there is a trade off between doping and the maximum practical length over which the high electron velocity can exist. These high velocities are well above the 1.2 x 10^7cm/s present in GaAs MESFETs. In low fields, n-type GaAs has equal collison frequencies with ions and phonons at 300^oK, when the donor density is 1 x $10^{17}/cm^3$. Thus for this usual level of 1 x $10^{17}/cm^3$ doping for FET devices, a source-drain spacing of .20-.25 microns is required, due to the ion scattering rather than the .40 microns for lightly doped GaAs, in order to obtain average drift velocity values of about 4 x 10^7cm/s. High energy electrons scatter less from the doping ions, so even with 1-5 x $10^{16}/cm^3$ doping in the drift region, the electrons ballistically injected by impulse acceleration show only modest additional scattering effects.

To show the application of some of these phenomena, three types of transistors were studied. One was the usual horizontal FET, constructed by a self-aligned, ion-implantation of contacts, using the gate metal, formed by electron beam lithography, as a mass. The gate metal was covered by a different metal, and plasma etching was used to give a "T" shape to the mask. This allowed a precise .1 micron spacing along the channel between the implanted contacts and the Schottky gate. Source-drain spacings down to .5 microns, with gate lengths down to .3 microns were constructed. Normally-off logic FET's were tested with .9 x $10^{17}/cm^3$ channel doping. These doped-channel GaAs MESFET's set a new state of the art for switching speed (15 ps) and power-delay product (2.4 femtojoules) for such devices. The results on this project, and the future extension of it to modulation-doped channels will be covered below.

Another device tested was the vertical FET with either gradual acceleration, or with ballistic electron injection using impulse acceleration. The technology and physical electronics of this type of device proved to be complex. The initial results, with working devices having modest g_m values for both versions, have been obtained and are covered below. The f_T values of over 24 GHz were readily

obtained, but goals of 100 GHz or more will take a considerable effort. Starting in August 1983 DARPA funded a three year contract at Cornell for this purpose.

The final device tested was the heterojunction ballistic electron bipolar transistor. In this NPN device, the emitter is made of $Al_xGa_{1-x}As$, which has a band gap larger than GaAs. There is a step in the conduction band at the heterojunction between $Al_xGa_{1-x}As$ and GaAs with a potential step of 1.06x volts, where x is the fraction of Ga atoms replaced by Al atoms. This potential step was used to launch ballistic electrons into the p type GaAs base in this bipolar transistor. For such ballistic electron transport across a .1-.2 micron base region, the electron velocity can be as much as 20 times as high as the usual diffusion velocity. In this effort at Cornell a new state of the art of $f_T \cong 15$ GHz was achieved for the bipolar. The f_{max} was usually < 5 GHz due to severe parasitic resistance in the base control. Again the technology and physical electronics required considerable effort, and a contract with WPAFB for a three year program is being negotiated.

II. Self-Aligned Short GaAs MESFET

This work was accomplished in cooperation with the Hughes Research Laboratory, and was able to exchange ideas and technologies to the advantage of both groups. Publications[1,2,3] on this project have been made to cover most of the progress to date.

The key positive results obtained are that the technique allows uniformity over a wafer, high speed and low power dissipation. One concern is that the output conductance of the devices rose approximately as the square of the reciprocal of the source-drain spacing. Thus values of maximum FET output resistance of 40 Ω-mm were obtained for .3 micron gate (.5 micron source drain spacing). This compares with the 300-400 Ω-mm maximum values on the usual 1 micron gate FET. Such low values of output resistance severely limit the voltage gain. Thus even with high current gain up to high frequency, the f_{max} will be limited unless a solution to this problem is found.

Two values of load resistance (1600 and 2600 Ω) as well as a saturated load were used with nominal 10 micron periphery FET's in

five-stage ring oscillators. In all cases a reasonable noise margin voltage swing was sought. The I-V curves for transistors are shown in Figure 1. The switching speed and the power dissipated are shown for a range of total bias voltage in Figure 2. With a shorter gate (.3 micron), 2.4 femtojoule power-delay product was obtained with .7 V total bias, but with larger switching time. About 5/8 of the capacitance of each stage is in the gate, and about 3/8 in the interconnection.

Although the effective source-drain spacing is about .4 micron in the shortest devices, the electron velocity was not raised anywhere near the ballistic limit because of the channel doping of .9 x $10^{17}/cm^3$. It would be necessary to reduce this source-drain length to .2-.25 micron in order to obtain such high velocity with all these ions causing collisions. An estimate of the average experimental electron velocity, at twice the knee voltage of the I-V curves, where parasitic output conductance effects do not mask the data, is 1.6 x 10^7cm/s for .75 micron source-drain distance (.55 micron gate length) and 1.4 x 10^7cm/s for .9 micron source-drain distance (.70 micron gate length). An ideal conduction channel, without donor ions in the path of the electrons, is that present in the modulation-doped heterojunction FET. If such a device also has an Al,GaAs buffer layer to suppress the output conductance in short devices, ballistic electron velocity in a .4 micron channel would be possible.

Such a modulation doped quantum well structure, shown in Figure 3, will be initially investigated during the remaining time on this project. Ion implanted self-aligned contacts also need study on this structure. It deserves a substantial effort over the next few years in order to obtain an easily integratable millimeter wave transistor as well as logic devices with less than 5 p.sec switching time.

III. Vertical Ballistic Electron FET

Experiments were initiated on these devices with gradual acceleration.[4] Channels doped at 7 x $10^{15}/cm^3$ and 5 x $10^{16}/cm^3$, reported earlier, were used to find the results of doping ions on the electron dynamics. The g_m values were low, as could be expected, for the lower doping, and the velocity was limited by collisions between

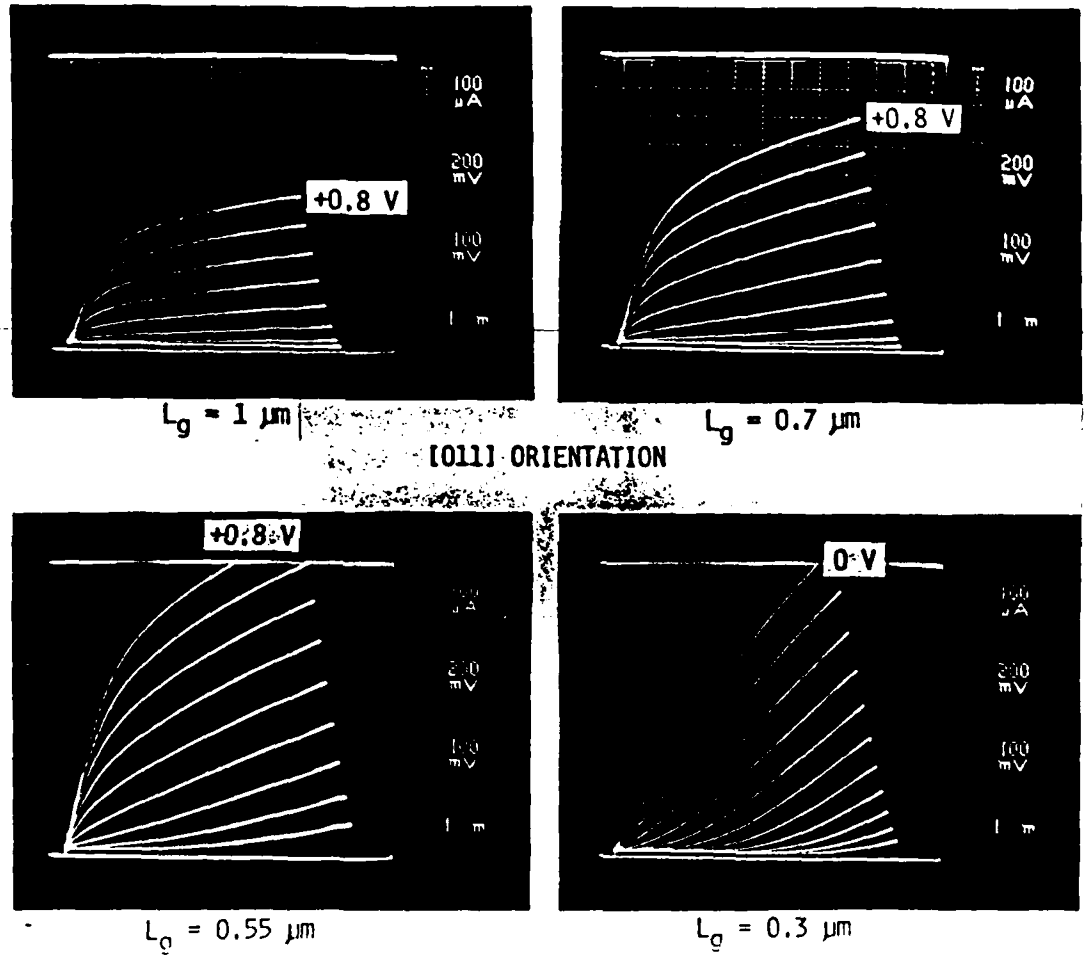

Figure *1* Drain characteristics for devices on wafer #321 with four different gate lengths in the (011) orientation.

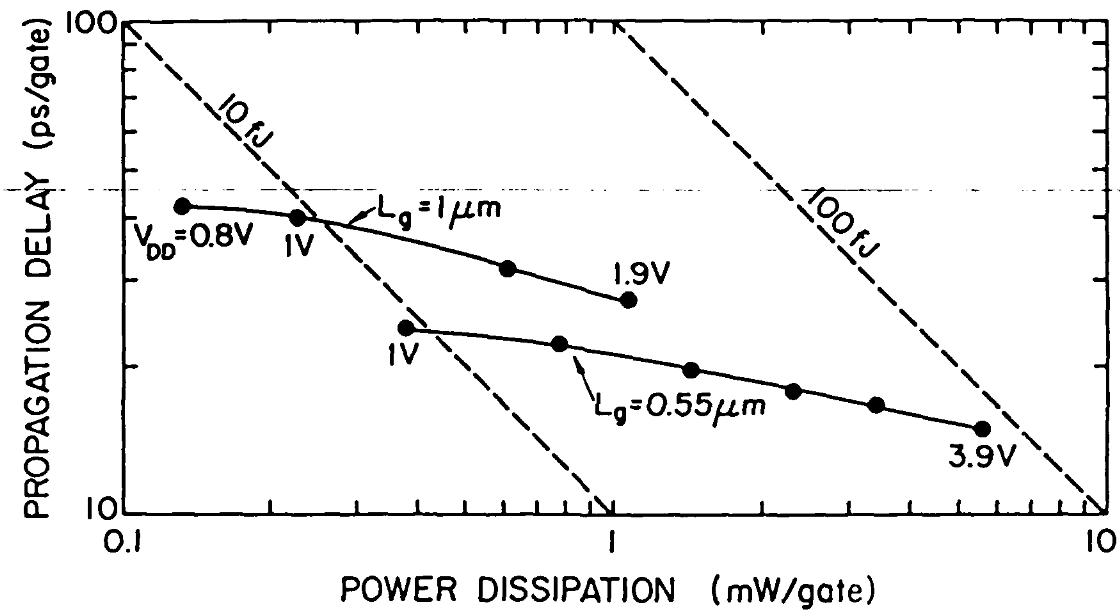

Figure 2 Delay-vs-power performance for ring oscillators with 1-μm and 0.55-μm-gate driver FET's and 1.6-kΩ load resistors.

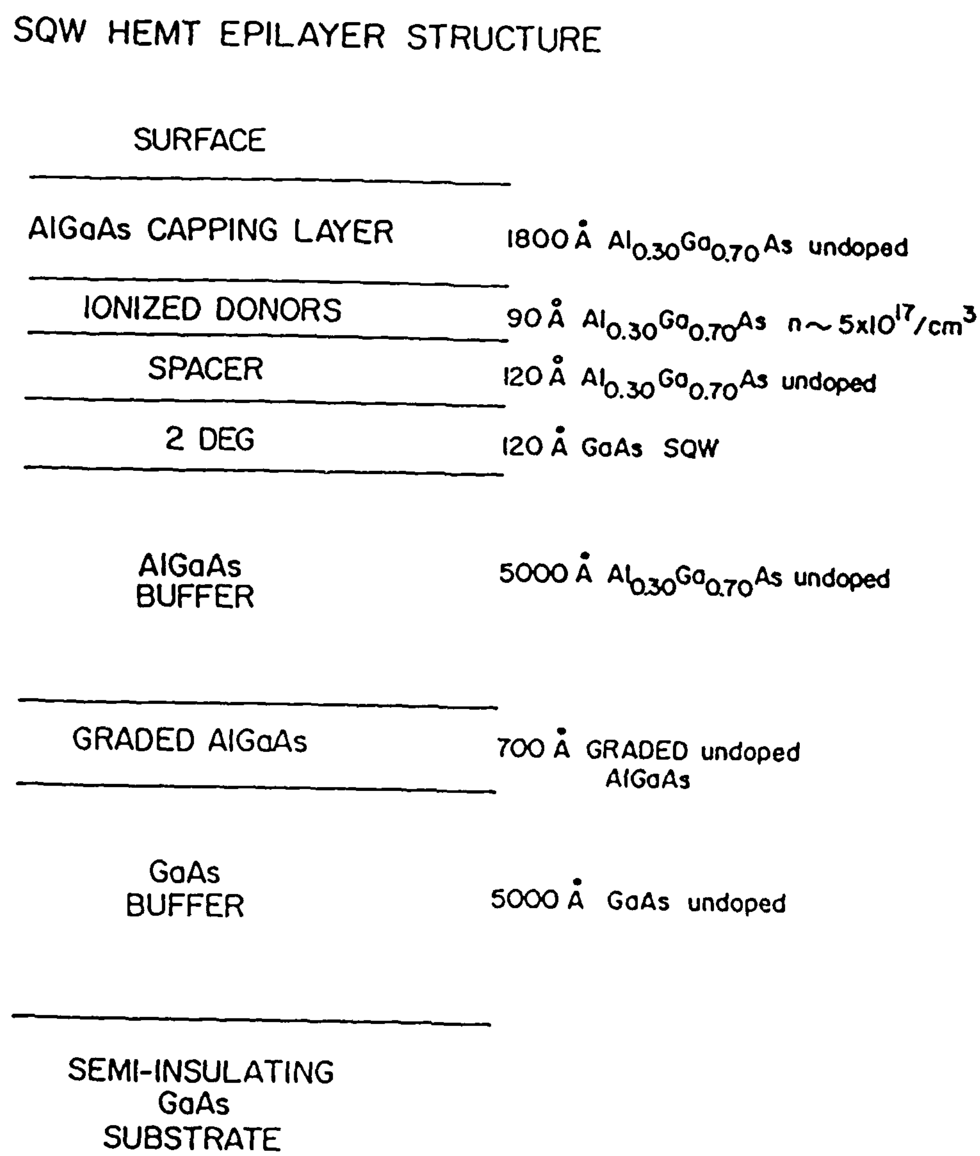

Fig. 3 Schematic cross section of a single quantum well HEMT.

electrons and ions in the case of the higher doping. The be results obtained were about 47 mS/mm and 81 mS/mm respectively, bo higher than standard FET's of these doping levels. Because of t small area of the top source ohmic contacts, shown in Figure 4, t source resistance is substantial, leading to g_m reduction by negati feedback. The period of this structure is 2 microns. The avera electron velocity estimates for these two cases are 3×10^7cm/s a 1.7×10^7cm/s for the low and high doping, respectively.

In order to launch the electron with a high velocity, heterojunction launcher was grown by MBE at the source. Using $Al_xGa_{x}As$ with x = .2 and doping of $1 \times 10^{17}/cm^3$, electrons could injected into a GaAs drift region doped at $2.5 \times 10^{16}/cm^3$. The I(showed a low turn on value of less than .15 V, note the .2-.25 expected. This is possibly due to impurity segregation at t heterojunction. This would limit the kinetic energy of the inject electrons. Limited injection current density values of 15-40 KA/cm rather than the $> 10^5$A/cm^2 desired, were also obtained, and we likely the cause of low average electron velocity. It is now expect that the ballistic electron density was also much lower than t donor in density. In order to correct this situation, donor densi values of $2.5 \times 10^{17}/cm^3$ or so in the Al,GaAs might be necessary. addition to verifying the heterojunction barrier potential drop. order to obtain higher frequency performance, the extension of th work on the DARPA project will use a 1 micron period structure ma with ultraviolet lithography.

IV. Ballistic Electron Heterojunction Bipolar Transistor

This initial work has been covered in some publications.[5,6] C key experienced researcher was supported by the French CN laboratory, of which he was a technical staff member on leave Cornell. In this device, the increased band gap of the Al,GaAs the emitter region can be used for either of two advantages, in trade-off situation. By broadly tapering the heterojunction, curr gain can be enhanced at the sacrifice of f_T. The extreme of this c at CNET is that the current gain of 20,000 was obtained at very frequency, but f_T was only around 2 GHz. If the Al composition

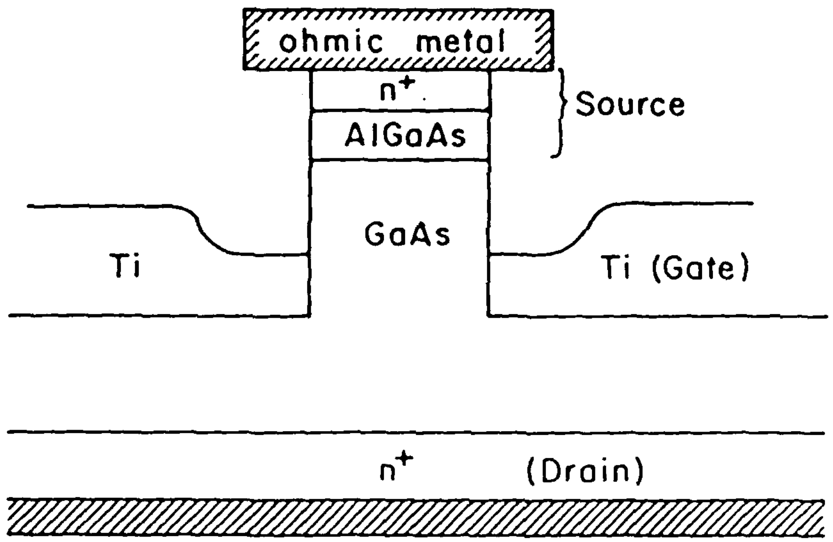

Figure 4

the heterojunction is varied steeply, lower current gains of less than 300 are obtained, the f_T is higher. At Cornell f_T values of about 15 GHz were first established for this device for this latter case. The simple device configuration, shown in Figure 5, was made to test the MBE grown heterojunction structures. Difficulty in obtaining low specific contact resistance values for the ohmic contact to the p-type base region limited values of f_{max} to a few GHz. These specific contact resistance values were about $10^{-3}\Omega$-cm , rather than the $10^{-6}\Omega$ -cm value desired.

A new technique developed at Hewlett-Packard[7] for obtaining $10^{-6}\Omega$ -cm^2 by Z_n shallow ion implantation and flash annealing will be useful in improving these results sharply. Experimental data for the ballistic electron bipolar lead one to conclude that the base transit time has been made nearly negligible compared to other physical effects, and that the reduction of parasitic resistance and capacitance require the most effort at present.

V. Conclusions and Recommendations

Because of its simplicity, the ultra short horizontal FET has achieved substantial results at Cornell and elsewhere. With the usual channel doping of $1 \times 10^{17}/cm^3$, the scattering of electrons by ions precludes reaching ballistic electron velocity values at .4-.5 micron source-drain length. Using a modulation-doped channel with no ions in the path of the electrons, average ballistic electron velocity values of 4×10^7cm/s should be possible at these source-drain distances. This should yield f_T values of 150 GHz or so. The high output conductance of these short horizontal MODFET's can be sharply reduced by using $Al_xGa_{1-x}As$ buffer layers, with $x > .40$, below the channel. This modulation doped quantum well structure should receive heavy effort for the next 2-3 years in order to obtain easily integrated millimeter wave transistors.

The ballistic electron injection vertical FET has great promise for even higher frequency performance, for the same source-drain spacing, due to a doubling of the average electron velocity. It requires substantial technological and physical electronic effort, and will be pursued during the next 3 years on a DARPA contract that

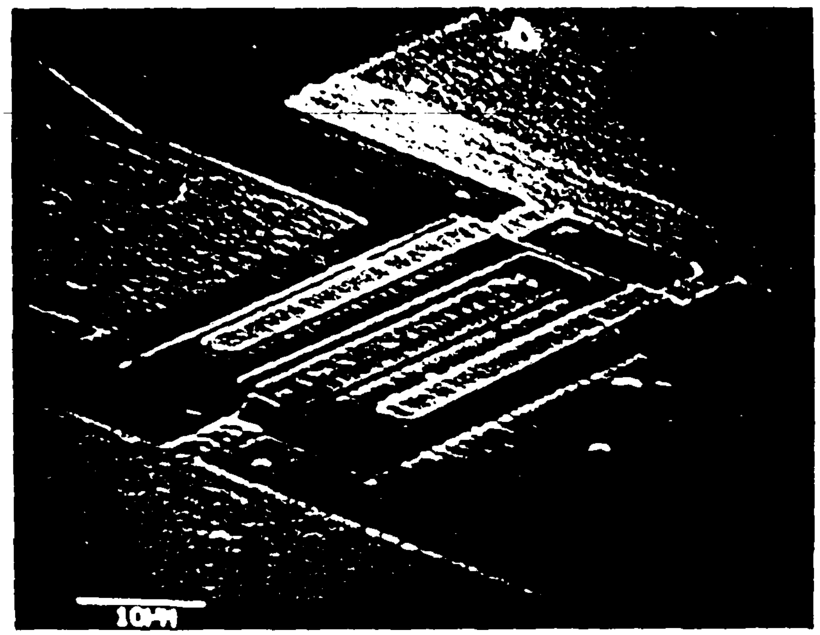

Figure 5 SEM photograph of Heterojunction Bipolar Transistor

includes substantial effort on ohmic contacts.

Finally, the ballistic electron heterojunction bipolar transistor also shows promise for high frequency operation. It has severe technological and physical electronic problems to overcome also. A three years contract effort with WPAFB is being negotiated to advance this device as much as possible.

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IV. Ballistic

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